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DOPPLER ULTRASONIC DETECTION OF INTRAVASCULAR BUBBLES DURING DECOMPRESSION FROM THE 1985 CAN/UK SATURATION DIVES TO 100 AND 360 MSW

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ABSTRACT

Four Royal Navy divers were monitored using Doppler ultrasound for intravascular bubbles during decompression from two saturation dives done at the Dive Research Facility at DCIEM. The depths of the dives were 100 msw and 360 msw, and the breathing gas was oxy-helium. The object of the monitoring was to provide diagnostic information to the diving medical officers responsible for the divers' welfare, and to collect information on the safety of the decompression profiles. The divers were monitored twice daily throughout the decompressions. In the first dive, no bubbles were detected at any time. In the second dive, bubbles were detected in all subjects around the depth of 100 msw, before a scheduled reduction in ascent rate from 1.5 msw per hour to 1.0 msw per hour. In two of the subjects, the bubbles were numerous. Throughout most of the rest of the decompression, few bubbles were detected.

INTRODUCTION

Doppler ultrasonic monitoring of divers for intravascular bubbles was carried out during the decompression phase of a 100-msw saturation dive at DCIEM in May 1985, and of a 360-msw saturation dive at DCIEM in July 1985.

The purpose of this bubble detection was twofold: to provide diagnostic information for the diving medical physicians responsible for overseeing the welfare of the divers, and to yield information about the stress from decompression experienced by the divers.

A brief review of the literature describing the results of monitoring earlier saturation dives follows.

Hamilton *et al.* [1] reported on findings from seven shallow air-saturation dives conducted at the US Navy Submarine Medical Research Lab (NSMRL) between 1973 and 1976. Doppler ultrasonic bubble detection was used to gauge the stress of decompression for both upward and downward excursions and for the final decompressions. It was also used after at least one gas switching experiment. Several excursions were made from 15.2 msw (50 fsw) to depths not greater than 70.1 msw (230 fsw), for periods not longer than one hour. Bubbles were detected on only one occasion during decompression from these brief downward excursions. For longer excursions, from 15.2 msw (50 fsw) to 30.5 msw (100 fsw) for 6-8 hours, bubbles were detected occasionally in most subjects. Several upward excursions to 1.5 msw (5 fsw) and 4.6 msw (15 fsw) from 15.2 msw (50 fsw) and 18.3 msw (60 fsw) were also done. During these upward excursions, moderate bubble counts were frequently observed, sometimes accompanied by skin-rashes and itching. Final decompression from the preliminary dive (*Pre-SHAD*) resulted in numerous bubbles preceding bends in both divers. In *SHAD I*, bubbles were detected in one of two divers. In *SHAD III*, bubbles were detected in two of three divers, and one of these two had a *Type-I* bend. No bubbles were detected during decompression from the three *NISAT* dives.

Eckenhoff *et al.* [2] [3] [4] at NSMRL, wished to determine the depths from which submariners, in a disabled submarine, could be transferred with safety to a deck recompression chamber. They observed 52 excursions to the surface from saturation on air in a hyperbaric chamber at depths from 13.7-19.8 msw (45-65 fsw). Doppler ultrasonic bubble detection was used to monitor both the excursions and the final decompression [5]. Low bubble counts were observed in about half of the divers during the final minutes of the excursions. There were a few incidents of decompression sickness, but there was no clear connection between the symptoms and the observation of bubbles. A bend that occurred during one final decompression was associated with high bubble counts.

Eckenhoff *et al.* [4] exposed 10 subjects to a pressure of 7.77 msw (25.5 fsw) for 48 hours, then returned them directly to the surface. Bubbles were detected in all subjects beginning two hours after return to the surface, and peaking four to six hours later. There were no cases of decompression sickness.

In another study, Eckenhoff [5] observed 18 subjects decompressing in 65 hours from a saturation depth of 40.2 msw (132 fsw) on nitrox. Four of the subjects had detectable bubbles. The subject with the most bubbles (Grade I at rest and III with movement [6] [7]) also experienced pain in both knees.

Barry *et al.* [8] described a 4.5 day saturation dive on nitrogen-oxygen at 50.3 msw (165 fsw), with daily two-hour excursions to 70.0 msw (200 fsw). Decompression was completed in 3.5 days, but five of the ten subjects showed symptoms of decompression sickness. Doppler ultrasonic bubble detection was done only for depths of 6.1 msw (20 fsw) and less. Bubbles were detected in all subjects, and two subjects had numerous bubbles (Grade III or IV).

Guillerm *et al.* [9] at the Centre d'Etudes et de Recherches Techniques Sous-Marines (CERTSM), reported on a dive by two divers of the French Navy to 300 msw in a hyperbaric chamber in 1975. Precordial bubbles were observed during the decompression after passing 200 msw. Low bubble counts were observed for the remainder of the dive until 20 hours after the surface was reached. The maximum bubble counts were observed at depths around 10 msw. No symptoms of decompression sickness were reported during the seven-day decompression.

Masurel *et al.* [10] used Doppler ultrasonic bubble detection during the *JANUS IV* saturation dives. A preliminary dive to 400 msw was made in a hyperbaric chamber. This was followed by a dive at sea to 430 msw. Downward excursions were made to 480 msw for the simulated dive and to 501 msw for the open-water dive. During final decompression, the bubble information was used to control the ascent rate. In the chamber, decompression was interrupted twice because bubbles exceeded Grade II at rest or Grade III with movement for at least one diver. During the decompression from the open-water dive the bubble grades never reached these levels, so the decompression was considered safe. Two divers, however, did experience mild joint pain. In the simulated dive, one diver had a *Type-II* bend after an excursion to 460 msw. This was accompanied by many (Grade III) bubbles at rest.

Masurel, Kisman, and Guillerm [11] reported on a simulated saturation dive to 450 msw involving eight subjects. The divers were monitored three times daily throughout the eleven-day decompression. Bubbles were detected in all subjects on occasion, and Grade-II bubbles (with movement) were detected in three of the subjects during much of the decompression. There were also several *Type-I* bends, which did not correlate well with the bubble observations, either in frequency or in time of occurrence. These authors felt, however, that, as in the previous dive [10], *Type-II* bends would correlate better with high bubble Grades, and that bubble detection could be used to guard against the occurrence of Type-II decompression sickness.

Masurel and Guillerm [12] reported on a second simulated saturation dive to 450 msw, *ENTEX V*, involving 4 subjects. The time at 450 msw was 12 days, and the decompression lasted 13 days 9 hours. Moderate-to-low bubble counts were observed during the middle stages of the decompression. These counts were lower than the counts for the earlier dive to 450 msw. Since there were also no cases of decompression sickness, Masurel and Guillerm concluded that the decompression profile was safe.

Masurel [13] reported the results of monitoring a saturation dive to 450 msw using a gas mixture consisting of helium with 0.85 % oxygen and 5 % nitrogen (*ENTEX*

VIII). During the bottom phase, experiments were done in which the divers breathed mixtures with different percentages of nitrogen (7.5, 10.0, and 0.0 %). Doppler bubble detection was used to determine whether bubbles could be observed as a result of counter diffusion following the gas switch. No bubbles were observed, however. Bubble detection was also done daily during the decompression phase. Compared with *ENTEX V*, bubbles were slightly more numerous and appeared earlier. Masurel recommended that, between 180 and 100 msw, the decompression-rate should be reduced slightly, or the partial pessure of oxygen should be increased slightly.

The final dive of the series, *ENTEX IX* [14], included six days at 450 msw followed by two days at 610 msw. Decompression lasted 23 days. The first bubbles were observed near 475 msw, reached a maximum at 450 msw, and then diminished slightly. They reached a second maximum at 250 msw, and then stayed at that level until the surface was reached. Typical bubble grades were Grade I at rest and Grade II or III with movement.

Masurel *et al.* [15] also looked for the appearance of bubbles resulting from switching either the breathing gas, or both the breathing gas and the ambient gas from hydrogen to helium at depths ranging from 120 to 300 msw. Low bubble counts were observed after about ten per cent of the exposures. High bubble counts were observed in one diver after a 240-minute exposure at 150 msw, in which both the breathing and ambient gas were switched.

Brubakk *et al.* [16] at the Norwegian Underwater Training Centre (NUTEC) reported on observations made during upward excursions to 250 msw from saturation at 300 msw. These authors used a dual-frequency, pulsed-Doppler instrument to check for bubbles in several veins and arteries. They observed venous bubbles in all six subjects, and numerous bubbles in several arteries, notably the ascending aorta and carotid arteries, in most of the divers. There were three cases of *Type-I* decompression sickness, but no instances of the more serious *Type-II* decompression sickness, often thought to follow from arterial bubbles [11] [17]. Later, Brubakk, Davies, and Daniels [18] reported the results of monitoring decompression from saturation at 350 msw, using both Doppler ultrasound and pulsed ultrasonic imaging. Bubbles were detected in five of six divers, and two cases of decompression sickness occurred.

DCIEM had done two saturation dives with Doppler ultrasonic bubble detection before the two reported here, and had participated in one saturation dive, using Doppler ultrasonic bubble detection, at the US Navy Experimental Diving Unit (NEDU). In an air-saturation dive to 15 msw done at DCIEM in February 1980, bubbles were detected in one of four subjects during decompression, shortly before he complained of pain in the left knee*. A second saturation dive at DCIEM was made in 1981. The dive was to 152 msw using helium, and involved five subjects. One purpose of the dive was to study the safety of upward excursions allowed by the USN tables developed by Spaur *et al.* [19]. Six upward excursions were made to 121 msw from the storage depth of 152 msw. Decompression to the surface continued from the last excursion. Doppler ultrasonic bubble detection was used to assess the stress felt by the divers during the upward excursions, and it was used to monitor the divers several

* Not previously published.

times a day throughout the decompression, lasting six days*. Two of the five divers produced high bubble grades (Grades II-III at rest) during the upward excursions and during the early stages of decompression. One of these subjects experienced knee pains about ten hours after the start of the final decompression. He was treated with oxygen and all subjects were recompressed by 10 msw, and held over night. For the rest of the decompression, bubble scores were moderate.

DCIEM also provided Doppler ultrasonic monitoring for a 305 msw (1000-fsw) saturation dive made by NEDU in 1981*. In this dive, decompression also started with an upward excursion. The step was from 305 msw (1000 fsw) to 253 msw (831 fsw). All six subjects were monitored immediately after this excursion, and bubbles were detected in all but the first to be monitored. One, in particular, had many bubbles (Grade III precordial at rest). This subject also experienced *Type-II* decompression sickness. All subjects were recompressed to the saturation depth. Subsequently, bubble detection was carried out two or three times daily for the remaining 12 days of decompression, but bubble scores were moderate. The association of Type II decompression sickness with large numbers of intravascular bubbles has been observed by Masurel *et al.* [20] [21] and by us [22] for bounce dives, and has recently been discussed by Eckenhoff [17].

PROCEDURES

The device used to check for intravascular bubbles was a continuous-wave ultrasonic unit designed specifically for the decompression application†. According to the manufacturer's specifications, they operate at a frequency of 5 MHz, and an intensity of 15 mW-cm^{-2}. The transducer probe is designed to be hand-held over the precordial region. The transmitting and receiving elements are angled to provide a region of maximum sensitivity about 5 cm in front of the probe.

The Doppler ultrasonic instrument was placed inside the hyperbaric chamber. The audio output was passed through a coaxial penetrator to an interface box on the outside (Fig. 1), which provided a connection between a cassette recorder, the Doppler unit, and the Diving Research Facility (DRF) communications system. A private channel was allocated for communication between the subject and the monitor, who could converse while both listened to the Doppler signal. It was necessary that the subject hear his signal to correctly place the probe. The Doppler signal and comments voiced by the observer were recorded on separate channels.

Three body sites were routinely monitored for bubbles. The right heart, was chosen because bubbles entering the venous system from any part of the body should be detected there. The subclavian (shoulder) veins, were chosen because, for these sites, there is little background noise in the absence of bubbles. Bubble signals from the subclavian veins are unambiguous, while bubbles in the heart can be obscured by background flow sounds, valve sounds, and heart-wall sounds. Bubbles detected in the

* Not previously published.

† The instruments were developed by the Institut National des Sciences Appliquées de Lyon, for the Centre d'Etudes et de Recherches Techniques Sous-Marines, Toulon, under contract with the French Direction des Recherches et Moyens d'Essais. They are manufactured under licence by Sodelec S.A. (Model DUG), Marseille, France.

subclavian veins soon reach the heart, but it has been observed that bubbles are frequently detected in the veins when they are not detected in the heart [22] [23], presumably because they are too small, or too few, to overcome the background signal there. (Although the subclavian veins lie closer to the surface than the region of maximum sensitivity for the transducer probe, this is partly offset by lower attenuation of the ultrasound owing to the shorter path length.) Other sites, such as the femoral veins, were not used to limit both the inconvenience to the subjects, and the time required for a monitoring session.

The subjects were required to place the transducer probe on themselves. Before the first dive, they were instructed in the correct placement of the probe, and several practice sessions were held. During the dives, the subjects were coached in finding the optimum probe placement. These steps are essential because the best position varies with different individuals, and poor probe placement can result in failure to detect bubbles.

During each monitoring session, the monitor listens to the audio signal produced as the output of the Doppler bubble detector while also recording the signal on a magnetic tape cassette. The subject first holds the probe over the precordium and, after the heart rate has settled to a resting rate, the observer records the signal for one minute. The subject is then asked to do a *kneebend*. This increases the blood flow, and may increase the number of bubbles for a short time, assisting in their identification. The movement is repeated twice at 30-second intervals. The subject next holds the probe over the right and left subclavian veins in turn, and a similar procedure is followed. The subclavian signal is recorded with the subject at rest for 30 seconds, and then while the subject does three clenches of the fist at 15-second intervals.

The observer grades the audio signal according to three criteria:

1. the number of bubbles detected per heart beat;
2. the number of heart beats containing bubbles, depending on case;
    a. for the rest case, the percentage of heart beats containing bubbles;
    b. for the movement case, the number of consecutive heart beats with the increased bubble signal;
3. the loudness of the bubble signal compared to the background.

For each of these criteria, the signal is assigned a classification labeled 0,1,2,3, or 4. These three sub-categories are then used to assign a global category, e.g., I, II-, II, II+, III-, ... , IV, by referring to a look-up table. This grading scheme was proposed by Kisman and Masurel [6] [7], and is similar to one used by Spencer [24], except that it provides a finer classification and considers more factors. Use of such a grading scheme helps to systematize the treatment of the bubble signals, and permits comparisons among different man-dives.

Before the dive, reference recordings were made during the practice sessions used to train the divers and check the equipment. Also, baseline recordings were made at the saturation depth, before the start of decompression. These reference recordings could then be compared with later recordings if bubbles signals were ambiguous. During the decompression phase, the subjects were usually monitored twice daily at 0930 and 1500 hrs. On two occasions during the second dive, the subjects were also

monitored at 2130 hrs.

Fig. 2 shows the pressure history of the dives. The breathing gas was a mixture of oxygen and helium. Throughout the first dive, and most of the second, the partial pressure of oxygen was 0.5 bar. It was reduced to 0.45 bar during the bottom phase of the 360-msw dive, and it was allowed to drop from 0.5 bar after 10 msw was passed during decompression.

RESULTS

A summary of the physical characteristics of the four subjects is given in Table 1. The weights and skinfold thicknesses are given for two dates separated by two months – before the first saturation dive and after the second. The per cent body fat was calculated using the method of Durnin and Womersley [25] for males between the ages of 20 and 29 years.

For the 100-msw saturation dive, no bubbles were detected in the subjects at any time during the decompression. It is of course possible that intravascular bubbles were present at times other than those chosen for monitoring, or that they were too small or too few to be detected. If present, however, it is unlikely that they were numerous.

The results for the second dive are summarized in Fig. 3., parts a–d. The figure shows the decompression profile and the times of monitoring. The initial rate of decompression was 1.58 msw per hour during the day, with no decompression between midnight and 0600 hrs. After the divers reached 100 msw, the rate was decreased to 1.0 msw per hour, and after 10 msw, it was reduced to 0.5 msw per hour.

The figures show the bubble grades for each diver for the precordial site only, because subclavian bubbles were not detected at any time during the dive. This suggests that the trunk and legs are the main sources of bubbles during decompression from saturation dives. The numeral to the left of the oblique represents the bubble grade at rest, while the numeral to the right represents the grade after movement.

After 40 hours of decompression, occasional bubbles were detected with movement in Diver no. 4. Eventually all subjects had some bubbles and Divers 3 and 4 had numerous bubbles. The first subject to show bubbles, Diver no. 4, continued to have the highest bubble grades – Grade II at rest and Grade III after movement. For all divers the peak occurred as they reached 100 msw, just before the decompression rate was decreased to 1.0 msw per hour.

Bubble scores tended to increase over the course of each day. On the two days just before the decompression rate was reduced to 1.0 msw per hour, an extra observation was made in the evening. The evening scores were higher than the afternoon and morning scores, demonstrating the cumulative effect of the day-long decompression. To gauge the effect of the nightly pause in decompression, the stop was delayed four hours at the 200-hour mark, so that the divers could be monitored in the morning, without disturbing their routine, just before resuming decompression. Although the bubbles decreased in number during the six-hour stop, they were still present in Divers 3 and 4.

After the decrease in rate of decompression to 1.0 msw per hour, the number of observed bubbles gradually diminished until, on the second day after the decrease in

rate, no bubbles were detected in any subject. This remained true until just before the next decrease in rate of decompression to 0.5 msw per hour, after the divers reached a depth of 10 msw. At that time, Grade 2 bubbles were detected in Diver no. 4 after movement. Following the decrease in decompression rate, no more bubbles were detected in any subject through to the end of the dive.

DISCUSSION

These results suggest that the profiles used were safe over all, but for the deeper dive, the decompression was becoming stressful for the divers by the time the 100-msw depth was reached. An earlier, more gradual decrease in decompression rate might prevent this. The six-hour stop at night reduces, but does not necessarily eliminate the bubbles. It may be advantageous to use a continuous decompression at a slower rate, such that the surface is reached in the same time. These changes might allow off-gassing to proceed without the formation of detectable intravascular bubbles. The decompression should then also be less stressful for the divers.

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Table 1. Physical Characteristics of the Divers

Subject Number	Age (years)	Height (m)	Weight (kg)		Sum of 4 Skinfolds (mm)		Per Cent Body Fat	
			Before	After	Before	After	Before	After
1	27	1.90	92.3	91.6	53.8	71.7	19.8	23.3
2	21	1.88	85.3	84.1	30.9	31.9	13.1	13.5
3	27	1.78	80.3	82.4	57.3	60.2	20.5	21.2
4	28	1.88	75.5	76.4	28.6	28.0	12.2	11.9
Mean	26	1.86	83.4	83.6	42.7	48.0	16.4	17.5
S.D.	3	0.05	7.2	6.3	15.0	21.4	4.4	5.6

Note:The measurements of weight and skinfold thickness were made on 14 May 85, before the first saturation dive, and on 23 July 85, after the second saturation dive.

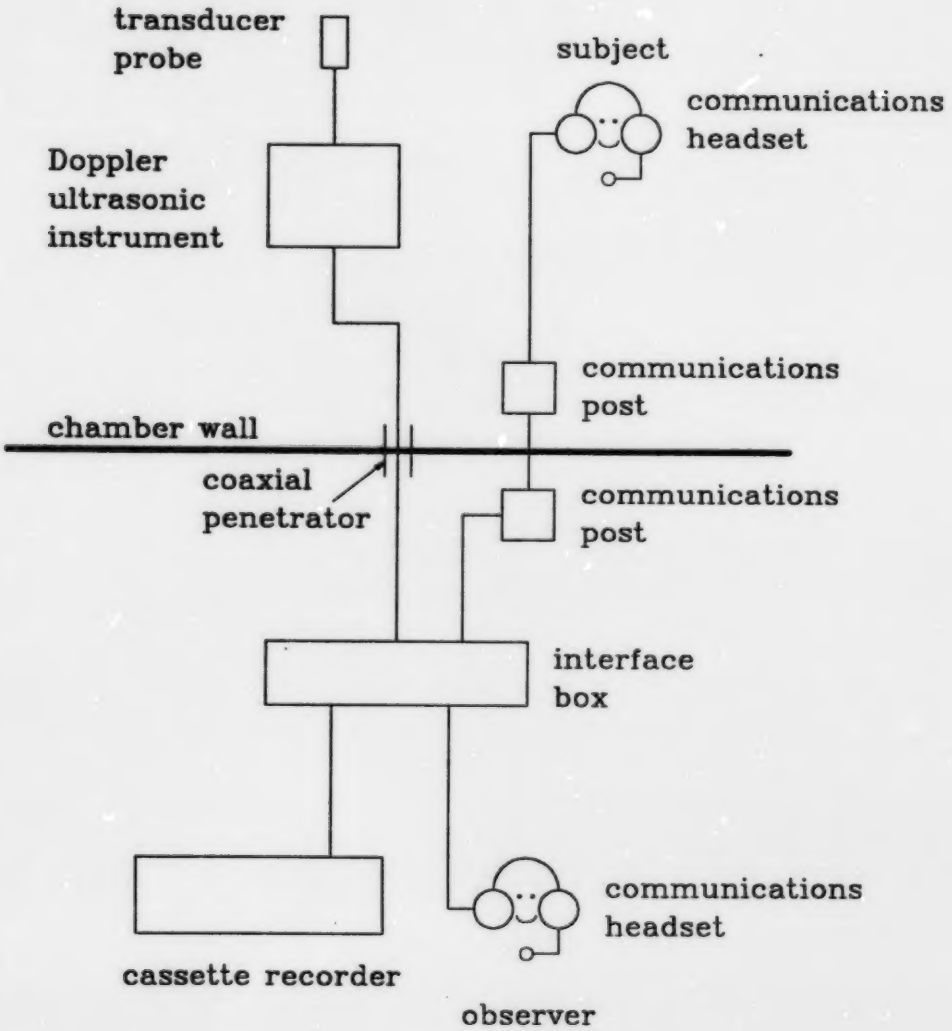

Fig. 1. The set-up for Doppler ultrasonic monitoring of subjects inside the hyperbaric chamber.

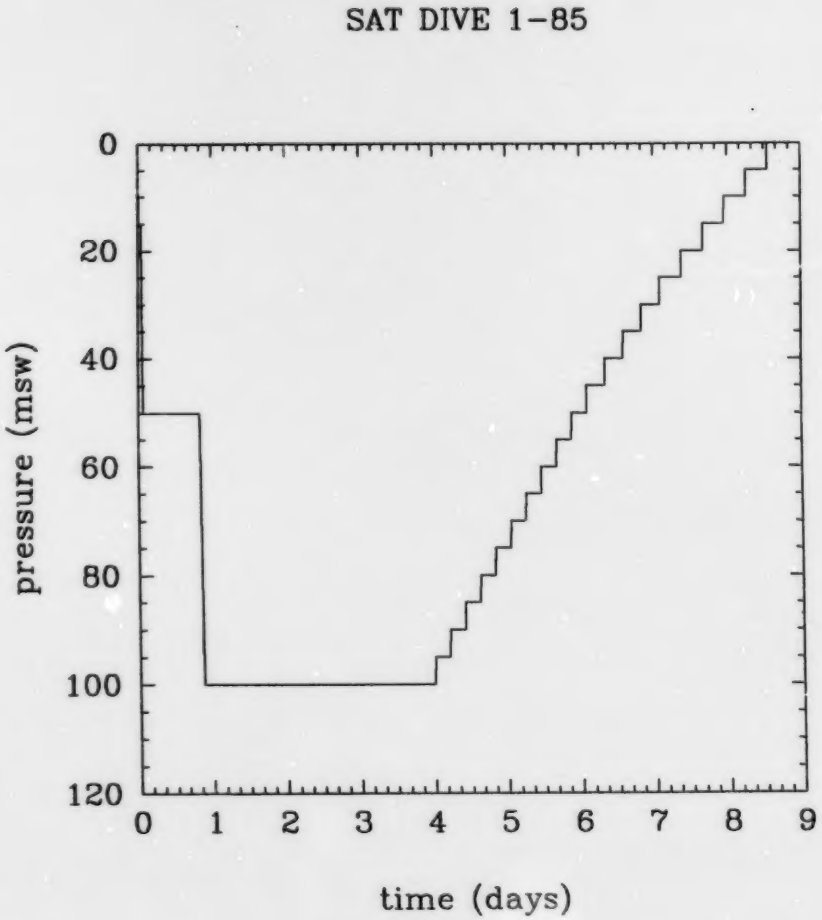

Fig. 2(a). The profile for SAT Dive 1-85.

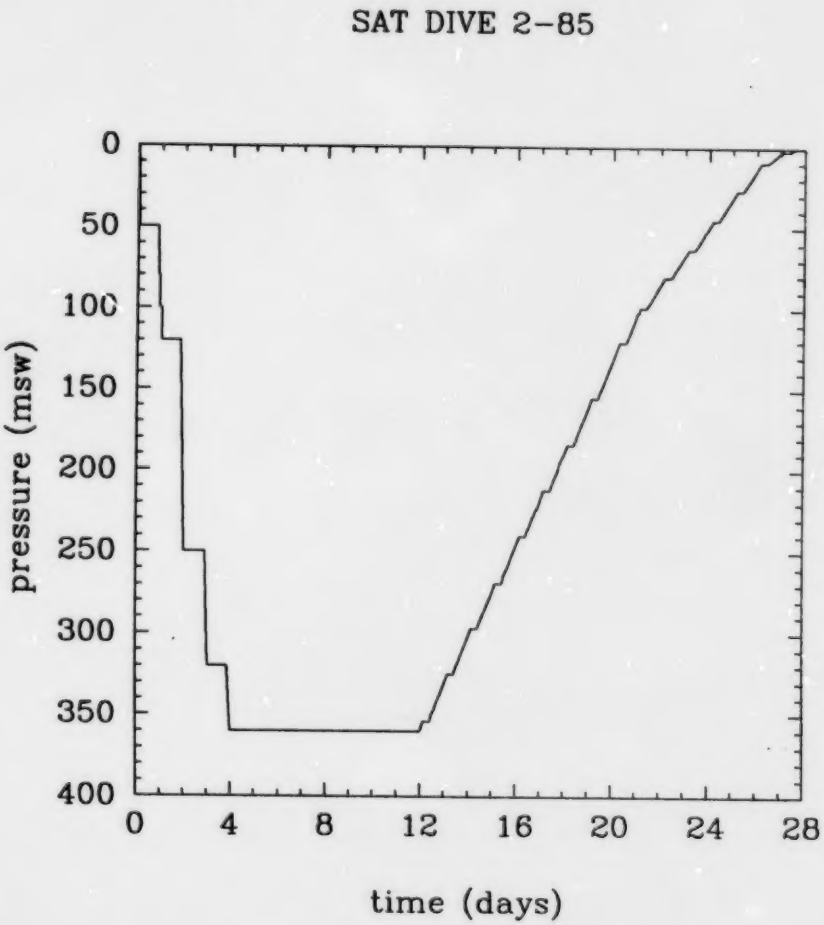

Fig. 2(b). The profile for SAT Dive 2-85.

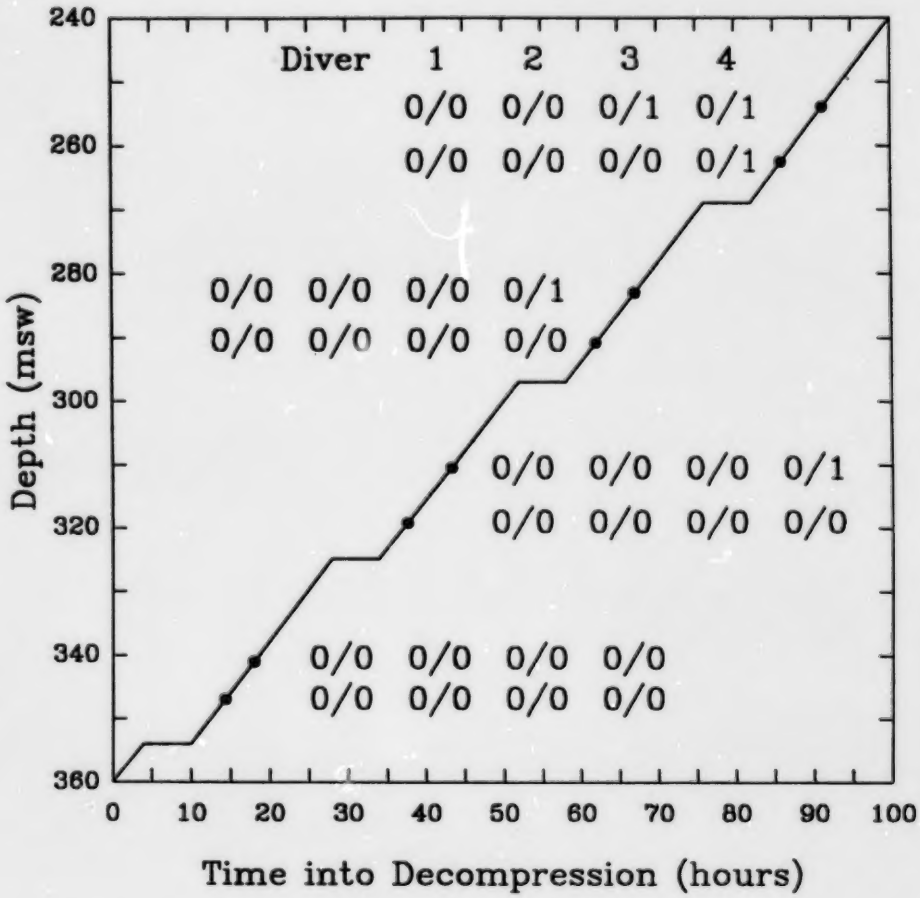

Fig 3(a). Precordial bubble grades at rest/after movement for the four divers during decompression in SAT Dive 2-85: 360 – 240 msw.

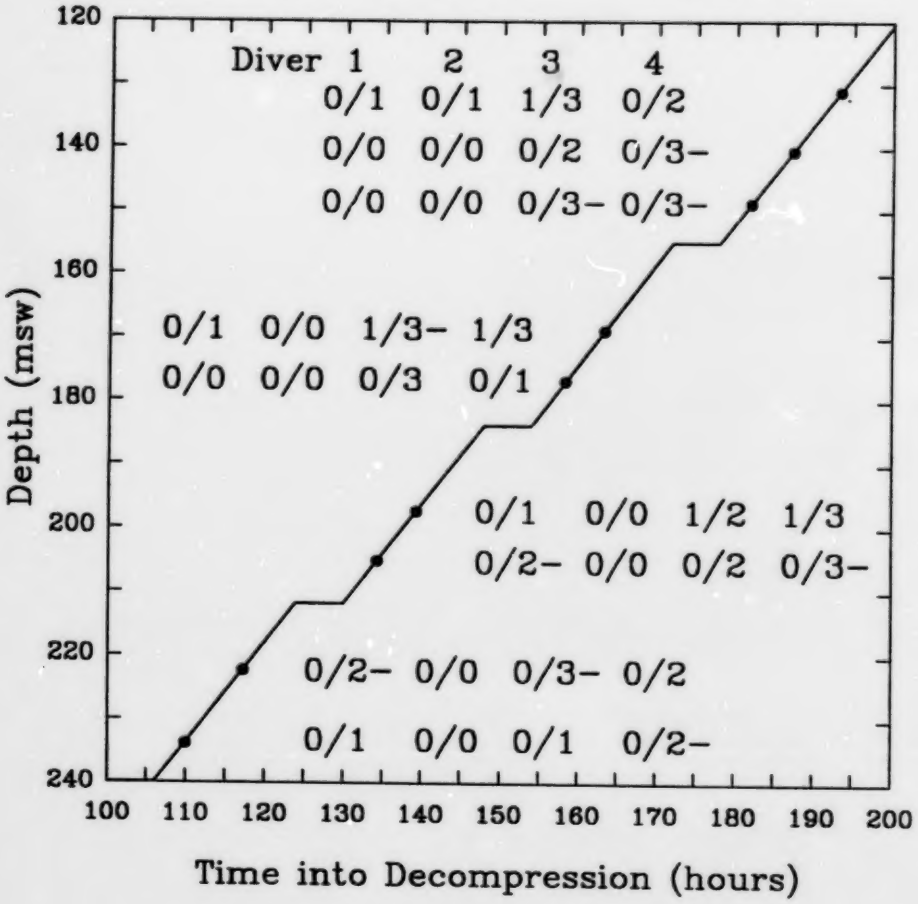

Fig. 3(b). Precordial bubble grades at rest/after movement for the four divers during decompression in SAT Dive 2-85: 240 – 120 msw.

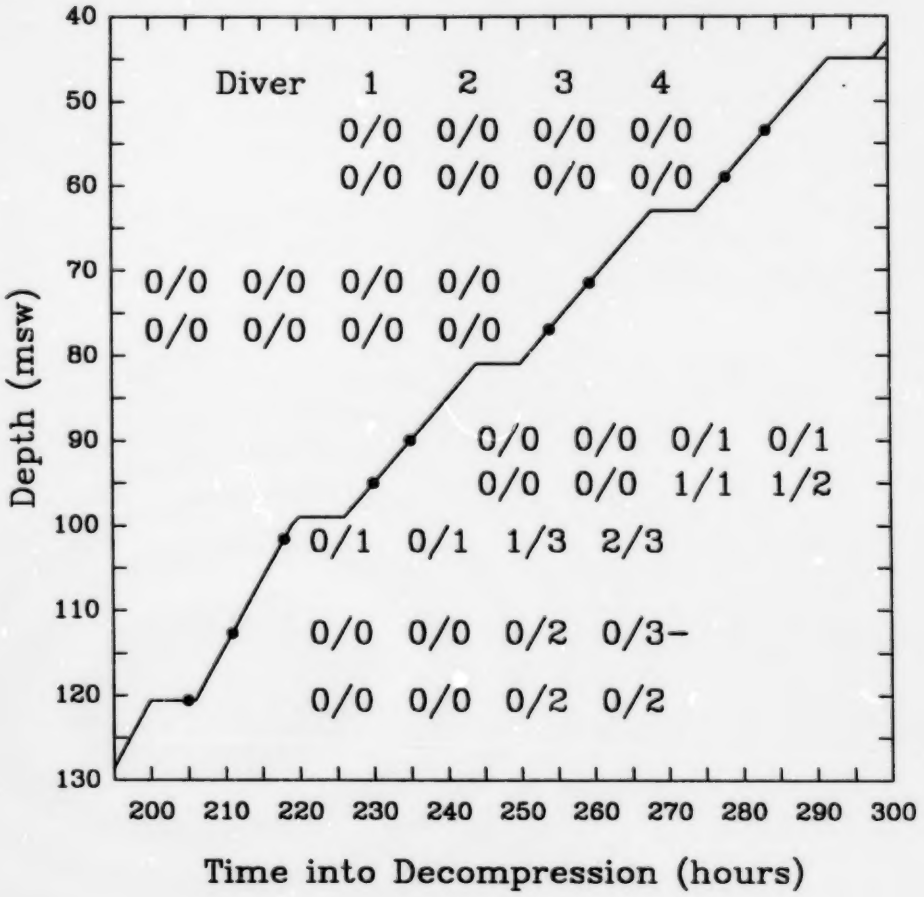

Fig. 3(c). Precordial bubble grades at rest/after movement for the four divers during decompression in SAT Dive 2-85: 128 – 43 msw.

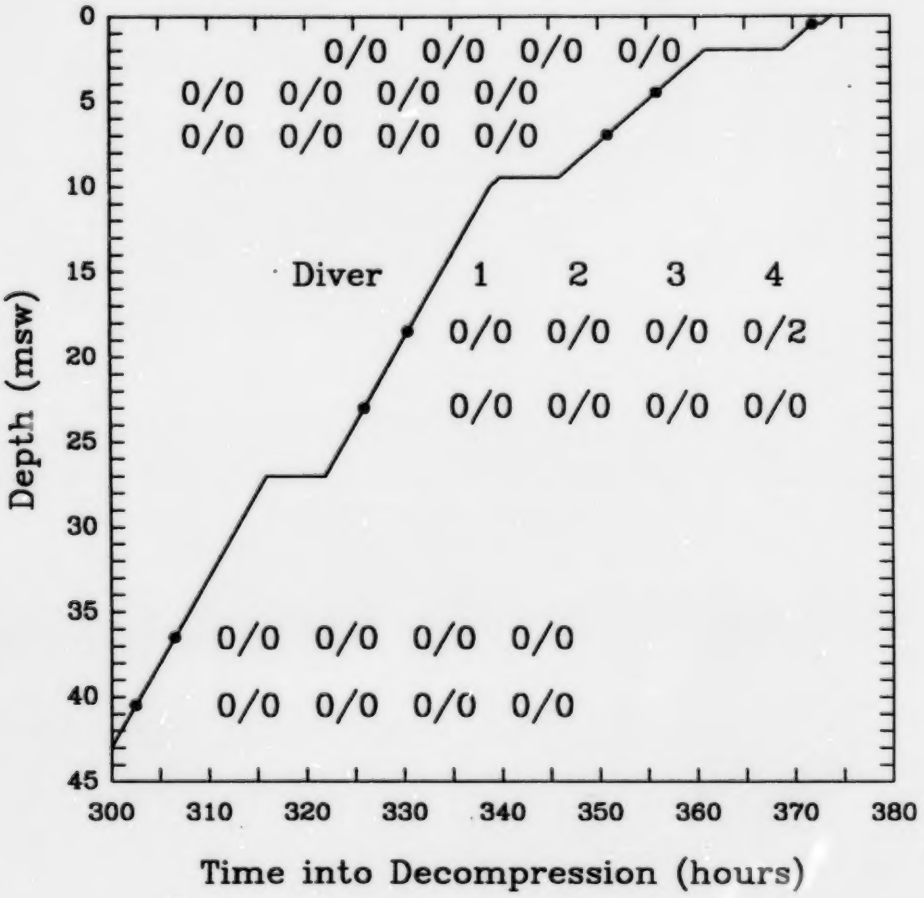

Fig. 3(d). Precordial bubble grades at rest/after movement for the four divers during decompression in SAT Dive 2-85: 43 – 0 msw.